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Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel. Volume 1 Passenger Cars and Light Trucks

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Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel

Volume I

Passenger Cars and Light Trucks

April 1990

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This report addresses the economic and environmental issues associated with the use of compressed natural gas as a motor vehicle fuel. Volume I analyzes the use of compressed natural gas as a fuel for passenger cars and light trucks. Volume II considers the use of compressed natural gas as a heavy-duty vehicle fuel.

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16. ABSTRACT

In July 1989 the President submitted to Congress his Administration's proposals for revising the Clean Air Act. One major component of his plan is the Clean Alternative Fuels Program. This program would replace a portion of the motor vehicle fleet in certain cities with new vehicles that meet stringent air emission limits operating on clean burning fuels such as methanol, ethanol, Compressed natural gas, liquified petroleum gas, electricity, and reformulate gasoline.

This report, released by EPA, is the second in a series of reports that will discuss the economic and environmental issues associated with each of these fuels.

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PREFACE

In July 1989, the President submitted to Congress his Administration's proposals for revising the Clean Air Act. One major component of his plan is the Clean Alternative Fuels Program. This program would replace a portion of the motor vehicle fleet in certain cities with new vehicles that meet stringent exhaust emission limits operating on clean-burning fuels such as methanol, ethanol, compressed natural gas, liquefied petroleum gas, electricity, and reformulated gasoline.

This report, released by EPA, is one in a series of reports that discuss the economic and environmental issues associated with each of these clean-burning alternative fuels.

This report discusses natural gas use in cars and light trucks. This application is emphasized because the first report in this series, the subject of which was methanol, also concentrated its emphasis on cars and light trucks.

Because natural gas has special features that also make it attractive for urban heavy-duty fleet applications, the Agency has prepared another report specifically treating the use of CNG in heavy-duty vehicles. This Volume II report is available under separate cover.

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ECONOMIC ASPECTS OF COMPRESSED NATURAL GAS USE

Current Natural Gas Prices

The current U.S. highway vehicle fleet is almost totally dependent on petroleum-based fuels.[1] Alternatives to petroleum-based motor vehicle fuels (i.e., gasoline and Diesel fuels) are of interest for two separate reasons. First, alternative fuels may contribute to a solution to air quality problems in the United States. A Vice Presidential Task Force Report issued in 1987 [2] detailed how the use of various neat and blended alternative fuels might contribute to a strategy designed to achieve the air quality goals of the Clean Air Act. President Bush's Clean Air Act proposals contain provisions for widespread utilization of alternate motor vehicle fuels including natural gas. Second, fuel substitution in the transportation sector could curb imported oil demand and help to restrain price rises as well as assure a reliable supply of oil from abroad.[3]

Natural gas, a gaseous hydrocarbon fuel, is composed primarily of methane (CH_4), but it may contain up to 20 percent higher weight hydrocarbons.[4] These hydrocarbons are primarily ethane, propane and butane. Minor other constituents include nitrogen, carbon monoxide, hydrogen sulfide and helium. Natural gas in compressed form (CNG) as an automotive fuel is the subject of this report.

One of the most important factors impacting the use of CNG as an automotive fuel is the price of natural gas fuel. A nominal value for the net heating value of Indolene fuel has been reported as 114,132 BTU/gallon.[5] The price of a gasoline energy equivalent of CNG at the retail price level, even for competing uses in the absence of a significant CNG motor fuel market, would be one indication of CNG's attractiveness to the consumer as an alternate transportation fuel.

Natural gas prices are typically presented in terms of a price per unit volume, or $/cubic foot.[6] To convert to $/energy equivalent, a factor for energy content per standard volume of natural gas must be used. The CNG fuel used in an earlier EPA report [7] had a calculated higher heating value of 1010 to 1032 BTU/SCF. The American Gas Association in a recent publication [8] listed 1031 BTU/SCF as a reference value for natural gas passing through major interstate pipelines. The heating value changes for CNG as its composition changes; for ease of comparison, however, a value of 1030 BTU/SCF was used here.

One frequently quoted index of wholesale prices is the price major interstate gas pipeline companies pay for gas. This price has two components: 1) the price of imported gas, and 2) the price of gas purchased from domestic producers. Table 1 contains a summary of price data for the years 1980-88 and the first eight months of 1989. This data, presented in $/1000 SCF, was taken from the Monthly Energy Review, a Department of Energy publication.[9] The conversion to $/mmBTU was accomplished by using the conversion factor of about 1030 BTU/SCF. To obtain an energy equivalent price based on lower heating value, the prices which used higher heating values were divided by 0.90. An explanation of this calculation has been given in an earlier EPA publication.[7] The data in Table 1 is presented in terms of 1989 dollars.

At an average 930 BTU/SCF lower heating value of natural gas, approximately 123 SCF of natural gas would provide an energy equivalent of 1 gallon of gasoline. The current prices in Table 1 may be considered a crude index of gas cost which a wholesaler pipeline company would use to base his delivery price to a retail operation. Using the average purchase prices listed for 1989, the current cost to a pipeline company for a natural gas thermal equivalent of 1 gallon of gasoline would be 26 cents. This estimate ignores cost changes that might be associated with increased natural gas usage as a transportation fuel such as operating expenses, capital recovery, and alternate sources of gas, however.

Another index of interest is the price of gas delivered to various categories of end users. Table 2 contains the average price of gas delivered to residential, commercial, industrial, and electric utility users over the same time periods referred to in Table 1. The data in $/1000 SCF was taken from Monthly Energy Review [9] and converted to $/mmBTU using the conversion factor given in reference 8. The conversion to prices based on the lower heating value for natural gas is explained in reference 7.

The prices in Table 2 for 1989 range from $2.61/mmBTU for delivery to electric utilities to $6.49/mmBTU, for residential end users. The residential delivered prices may be relevant for a scenario which involves refueling vehicles with natural gas overnight using a home-based compressor. Commercial or industrial prices may be more relevant for customers who purchase large volumes of natural gas, such as large fleets or refueling stations.

The prices for delivery to consumers vary considerably by region within the United States. The American Gas Association [8] has published average U.S. consumer gas prices by region for the quarter ended December 31, 1988. For residential end users, these prices, based on higher heating values, varied

Table 1

Average Natural Gas Prices
Major Interstate Pipelines Average Purchase Price

Higher/Lower Heating Value Prices (1989 $)

Year	Imports ($/mmBTU)	Purchased From Producers ($/mmBTU)
1980	6.39/7.10	2.36/2.62
1981	6.38/7.09	2.84/3.15
1982	6.12/6.80	3.37/3.75
1983	5.38/5.98	3.50/3.88
1984	4.70/5.22	3.35/3.72
1985	3.57/3.96	3.19/3.54
1986	2.75/3.06	2.60/2.89
1987	2.29/2.54	2.21/2.46
1988	2.06/2.29	2.17/2.41
1989 (Jan-Aug)	1.96/2.18	2.07/2.30

mmBTU = Million BTUs.

Table 2

Average Price of Gas Delivered To Consumers

Higher/Lower Heating Value Prices

Values Given In $/mmBTU, Adjusted To 1989 $

Year	Residential	Commercial	Industrial	Electric Utilities	Overall Averages
1980	5.32/5.92	4.90/5.45	3.70/4.12	3.28/3.65	4.21/4.68
1981	5.66/6.29	5.28/5.86	4.14/4.60	3.81/4.24	4.63/5.14
1982	6.41/7.12	5.98/6.64	4.80/5.33	4.31/4.79	5.36/5.95
1983	7.23/8.03	6.67/7.41	4.99/5.54	4.27/4.75	5.75/6.39
1984	7.05/7.83	6.39/7.10	4.86/5.40	4.26/4.73	5.58/6.20
1985	6.84/7.60	6.15/6.83	4.42/4.91	3.97/4.41	5.28/5.86
1986	6.35/7.05	5.53/6.14	3.52/3.91	2.65/2.94	4.50/5.00
1987	5.84/6.48	5.02/5.58	3.10/3.44	2.44/2.72	4.27/4.74
1988	5.59/6.21	4.73/5.25	3.01/3.35	2.39/2.66	4.18/4.64
1989 (Jan-Aug)	5.84/6.49	4.61/5.12	2.81/3.12	2.35/2.61*	4.01/4.45*

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mmBTU = Million BTUs.

* January - July 1989 only.

from $4.49/mmBTU to $7.04/mmBTU, with the higher prices found in the northeast region of the U.S. It may be expected, therefore, that prices of natural gas for vehicle fuel usage could vary considerably by region because of differences in prices of gas from various sources, pipeline distribution, and operating costs. In addition, the spot market for natural gas can be low, thus offering some price advantages, but by its very nature the spot market price may not be a reliable indicator of high continuous demand such as that provided by vehicular use.

An earlier U.S. EPA Special Report [10] has noted that the price at which natural gas is available is dependent upon the price of competing energy sources, the existence of alternative markets for gas, and the cost of collecting and transporting the gas. In more remote regions, such as Prudhoe, Bay, Alaska, natural gas is coproduced with oil and is reinjected back into the wells at a cost because at current and expected prices it is not economic to produce and transport this "remote" natural gas. A presentation by SRI International [11] quoted in the aforementioned Special Report [10] assumed that natural gas could be available at Prudhoe Bay for less than $0.50/mmBTU over the next 20 years. A recent U.S. DOE analysis [12] suggests that prices ranging from $0.50-1.00/mmBTU for remote natural gas appear reasonable.

The overseas transportation and port costs to receive remote natural gas in the form of liquefied natural gas (LNG) may be considerable, however. DeLuchi, et al., in a recent comprehensive analysis of resource supply issues relating to natural gas vehicles,[13] stated that the high capital cost of liquefaction plants, competition for the gas between importing nations, and uncertainty over the size of reserves have increased the price of LNG from remote natural gas. At the domestic level, natural gas prices necessary to make substantial increases in the amount of imported LNG attractive might make the recovery of unconventional reserves of domestic natural gas competitive in price. DeLuchi [13] states that both the American Gas Association (AGA) [14] and the Energy Information Administration [15] project negligible increases in the amount of LNG imports over the next 10 to 25 years.

Assuming that the importation of LNG was economically desirable, the U.S. could not import more than 1 TCF/year at present.[13] Only one U.S. LNG terminal is now in service, at Everett, Massachusetts. Three other facilities, in Maryland, South Carolina, and Louisiana, are currently on standby. DOE has stated that a considerable expansion of terminal capacity and corresponding infrastructure would be required for a major expansion of LNG imports into the U.S.[12] DeLuchi [13] also notes that the U.S. public generally opposes new LNG terminals on safety grounds, though some experts argue that such risks are very small.

The U.S. Department of Energy (DOE) is studying natural gas pricing with respect to a natural gas vehicle market, which may expand significantly as a result of the Administrator's proposed Clean Air Act Amendments. AGA has published projected natural gas fuel prices to the year 2005; [16] a portion of their projections are reproduced here as Table 3.

Table 3 projects the price of natural gas delivered to service stations in the year 1995 in 1989 dollars. The prices listed take into account distribution margins and incorporate wellhead price projections. Price projections are given for eight separate regions; these regions might benefit substantially from the introduction of alternative fuels because of higher ozone concentrations.[16]

No attempt is made here to weight price according to projected sales volumes by region. The prices range from a low of $2.59/mmBTU (lower heating value) in Texas to $5.89/mmBTU in Connecticut. A simple average among the regions listed here is $4.66/mmBTU. These prices are used later in this report to develop a cost to consumers for natural gas vehicle fuel. The range of prices above approximates the current low utility and higher commercial use price range given in Table 2. The AGA has also made an attempt to predict differences in gas price based on geographic location. The geographic locations are major urban areas where concentrations of ozone in the ambient air are of great concern.

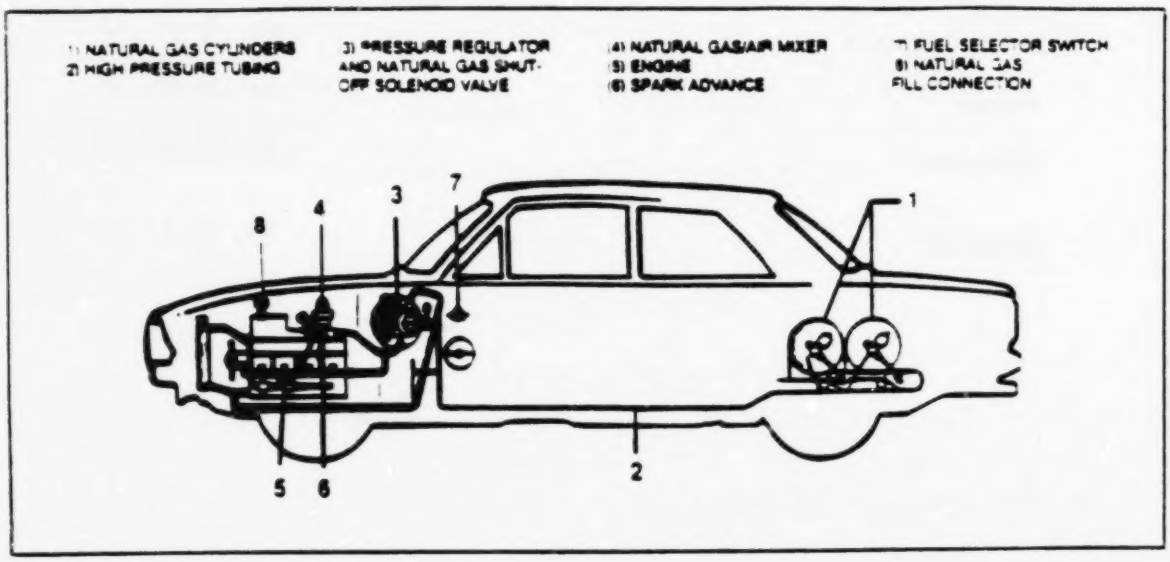
In this report, estimates are made of the gasoline equivalent price per gallon for natural gas as a vehicle fuel. The price of natural gas, like that of all fuels, is determined based on supply and demand for natural gas as well as the price for competing fuels in the marketplace. For transportation fuels, the dominant fuels are petroleum-based, and therefore oil prices will have a large influence on the eventual price of natural gas as a vehicle fuel. Since no consensus exists on the most likely trend for future oil prices, no long-term forecast of either future oil or natural gas prices is made here. Instead, current or near-term estimates for prices are used.

Dual-Fuel Conversion and Dedicated Vehicle Costs

Two types of CNG vehicle configurations are considered in this report: 1) a dual-fuel vehicle, originally configured to operate on gasoline but converted to selective operation on CNG or gasoline fuels, and 2) a vehicle dedicated to operation solely on CNG and optimized for its use.

The conversion of gasoline-fueled vehicles to dual-fuel usage with CNG is an established technology; there are more than 30,000 gasoline-fueled vehicles in the U.S. converted to run on natural gas.[17] Several companies currently offer conversion kits and the services to install the additional hardware on the vehicle to be converted.

Figure 1



Additional Components And Systems Necessary To Convert Gasoline Fuel Vehicles To CNG (Dual Fuel) Usage

Table 3

Projected Delivered Natural Gas Price
To Vehicle Refueling Stations (1989 $/mmBTU)

Region (State)	Year 1995 Higher/Lower Heating Value Prices
California	$4.81/$5.34
Connecticut	$5.30/$5.89
Illinois	$3.46/$3.84
Maryland	$4.88/$5.42
New York	$4.66/$5.18
Pennsylvania	$3.98/$4.42
Texas	$2.33/$2.59
Wisconsin	$4.14/$4.60
AVERAGE	$4.20/$4.66

A dual-fuel vehicle must be set to operate on one of the fuels prior to cold start. When the vehicle's fuel selector switch is set to the natural gas mode, gas leaves the vehicle storage cylinders and passes through steel tubing to a pressure regulator where it is reduced to near atmospheric pressure. The natural gas from the regulator flows into a gas/air mixer where air and natural gas fuel are mixed and drawn into the engine. A spark advance control for natural gas operation is added to the engine, and the fuel selector switch is mounted in the passenger compartment. A diagram of some typical retrofit components is given here as Figure 1.[18]

There are three significant costs associated with conversion of a gasoline-fueled vehicle to dual-fuel usage with CNG. First, there are "underhood" modifications that must be made to accommodate the introduction and mixing of the gaseous fuel with air. These modifications include the installation of shut-off valves, fuel selector switches, gauges, pressure-reducing valves, and a carburetor designed for use with natural gas.[19,20] Second, the labor costs associated with the conversion are substantial. This is primarily due to the fact that current conversion efforts involve relatively small vehicle fleets. Larger numbers of vehicle conversions may involve significant economies of scale.

Finally, the use of CNG involves the pressurized storage of natural gas onboard a vehicle. CNG's low energy density relative to gasoline necessitates the use presently of large, bulky storage vessels. Weaver [21] has noted that the weight of a conventional steel cylinder containing the energy equivalent of 1 gallon of diesel fuel weighs 41 lbs; the weight of the fuel and tank for a typical gallon equivalent of diesel fuel is only 9.2 lbs. Although promising research is underway in the area of lighter weight and more compact storage media, this technology is not yet commercial, [13,21] and the heavy gas storage cylinders required to meet U.S. Department of Transportation safety requirements are a significant additional cost and vehicle weight consideration.

Table 4 contains a range of costs for these components for three different scenarios: 1) light-duty automobiles at 3,000 psi onboard fuel storage pressure, 2) light-duty trucks at 3,000 psi gas storage pressure, and 3) light-duty automobiles at 2,400 psi storage pressure. These costs were developed from several conversion supplier quotes.

Generally, total conversion costs decrease with increasing vehicle size for a particular application (e.g., light-duty automobiles). This is primarily due to the larger engine compartments and trunk space associated with larger vehicles (e.g., full-size versus mid-size passenger cars). It is easier to install the bulky storage vessels and underhood hardware on vehicles with large engine compartments and roomier trunks. An attempt to quantify this difference within a particular

Table 4

Costs to Convert Light-Duty Vehicles to Dual-Fuel Status

Scenario - Component	Cost Range
Light-duty automobile (3,000 psi storage):	
Underhood equipment costs	$ 650 - 750
Labor to install components	700 - 900
Compressed gas storage bottles	1,200 - 1,600
Cost Range	$2,550 - 3,250
Light-duty truck (3,000 psi storage):	
Underhood equipment costs	$ 650 - 750
Labor to install components	500 - 700
Compressed gas storage bottles	1,200 - 1,600
Cost Range	$2,350 - 3,050
Light-duty automobile (2,400 psi storage):	
Underhood equipment costs	$ 650 - 750
Labor to install components	700 - 900
Compressed gas storage bottles	300 - 600
Cost Range	$1,650 - 2,250
Cost estimates for CNG-fueled vehicles in mass production:	
Dual-fuel (CNG plus gasoline)	$1,600
Dedicated (CNG only)	$ 900

application is not made here; this, however, should explain the difference in conversion costs between light-duty truck and automobile applications in Table 4.

The data in Table 4 assumes that fiber-wrapped steel or aluminum tanks are used in place of conventional steel tanks for 3,000 psi storage. Fiber-wrapped tanks offer a savings of approximately 30 percent in cylinder weight over conventional steel tanks, but are more expensive.[21] Advanced fiber-wrapped aluminum cylinders and all-composite cylinders may offer even greater weight savings in the future.[13] Storage costs are greatly reduced at 2,400 psi storage pressure; however, driving range is reduced with 2,400 versus 3,000 psi storage bottle pressure.

The costs in Table 4 are presented in a range of values for vehicles typically representative of those found in each category; vehicles having either very large or very small interior volumes are not represented here. (The conversion cost of a two-passenger vehicle may exceed $5,000, for example.)[22] Any economies-of-scale associated with larger scale conversion of vehicle fleets to dual-fuel usage are not discussed here. Large-scale production of dual-fueled vehicles (CNG/gasoline) would involve the efforts of one or more major automotive manufacturers.

Costs similar to these have been quoted in the literature. A 1983 study [23] used a range of $1,200-1,900 for the conversion cost of a light-duty vehicle to dual-fuel capability. In 1988, the Gas Research Institute estimated the cost of converting a gasoline vehicle to CNG dual-fuel capability at $1,500-2,100 per vehicle.[24] Other authors have quoted conversion costs at $1,200-1,500 per vehicle.[25,26]

Dual-fuel CNG-gasoline vehicles like other dual-fuel vehicles suffer from several drawbacks associated with their ability to run on gasoline fuel. The weight of the compressed gas cylinders large enough to provide at least a 250-mile driving range on CNG alone is significant and results in a fuel economy loss particularly if the vehicle is also operating with a full tank of gasoline (gasoline fuel usage). Useful vehicle space is reduced when compared to a gasoline vehicle due to the volume restrictions posed by the inclusion of both liquid and gaseous fueling components. Finally, engine power and efficiency on CNG fuel are not optimized if the base engine is configured for gasoline-fueled operation.

If a CNG dual-fuel vehicle was to be mass-produced by a vehicle manufacturer, costs may be reduced due to high production volumes and more efficient labor utilization. We estimate that such vehicles would still cost $1,600 more than the baseline gasoline-fueled car.

An optimized CNG vehicle (single-fuel only) would use a higher compression ratio in order to take full advantage of CNG's higher octane rating (relative to gasoline). Ignition timing and valve timing could also be optimized for CNG usage. Gasoline fuel components such as the carburetor or fuel injection system, fuel pump, and gasoline tank would be eliminated, offering weight, volume, and abate the cost increase. The new fuel tanks could also be tailored to the vehicle design, making more efficient use of existing space on the vehicle.

Very few working examples of dedicated CNG vehicles exist, however. Ford produced several light trucks during 1984 modified to operate exclusively on CNG.[27] These were not built in substantial volume, however, so it is necessary to use gas industry estimates for the cost of dedicated vehicle production. Incremental costs per vehicle quoted for an optimized CNG vehicle range from $500 to $1,100.[23,28,29] Further refinement of these estimates depends on the decision by major automakers to produce a dedicated CNG vehicle for public sale and advancements in CNG-related engine technology. Our estimates of dedicated CNG vehicle costs are about $900 more than its gasoline-fueled counterpart in mass production.

Service Station Retrofit Costs

One of the key obstacles to penetration by CNG in the U.S. transportation fuels market is the virtual nonexistence of a CNG maintenance and refueling infrastructure, a critical disadvantage relative to gasoline.[19] There are approximately 30,000 vehicles equipped to run on natural gas in commercial use in the U.S. [13,17] supported by a network of 275 private refueling stations. Only 15 of these stations offer natural gas for sale to the public, however. The U.S. Department of Energy has estimated that displacement of 1 million bbl/day of petroleum-based transportation fuel by CNG would involve coverting 15,000 regular public service stations and 2,000 truck stops to distribute CNG fuel.[30] Similarly, Bechtold [30] has estimated that replacement of 2 million bbl/day of petroleum transportation fuel demand with natural gas would require approximately 35,900 public light-duty filling stations as part of a CNG refueling infrastructure.

Both of the scenarios above concerning petroleum fuel demand displacement by compressed natural gas fuel are substantially greater than the market penetration assumed in the President's recent Clean Air Act revision proposals. No attempt is made in this report to reconcile differences in market displacement assumptions among various authors. The published studies above may have assumed a particular significant displacement scenario without taking into account specific proposed legislation. All of these estimates are

large enough, however, to ensure at least some realization of economies of scale associated with costs related with the introduction of compressed natural gas as a serious alternative to petroleum-based transportation fuel.

Three types of CNG vehicle refueling options are available. First, slow-fill refueling stations use a compressor with limited or no storage capability. The compressor is sized to provide filling capacity for a given number of vehicles over a predetermined downtime. One potential use of the slow-fill concept is at a refueling point for a vehicle fleet where downtime occurs at regular, predictable intervals.

Home refueling may be a refueling option for residences served by residential gas lines. Small compressors could operate from lower residential delivery pressures (near atmospheric) and pressurize CNG fuel tanks to 1,000-3,000 psig.[13]

The third option involves fast-refueling from on-site storage capacity at the filling station. The compressor that pumps pipeline gas to storage vessel pressures must be sized to ensure that peak demand is satisfied. Currently all public refueling stations in the U.S. use the fast-fill method.

Assumptions concerning the characteristics of a network of CNG public refueling stations must be made. For the DOE 1 million bbl/day gasoline demand replacement scenario, the stations are assumed to be partial conversions of existing gasoline vehicle refueling facilities; no land acquisition costs for additional filling stations are contemplated. These public-filling stations would be designed to service approximately 300 vehicles a day, with a peak capacity of 30 vehicles per hour. Four fueling nozzles per station and a refueling time of 8 minutes per vehicle are assumed. Deluchi,[13] citing Canadian experiences,[32] has estimated that refueling time for a CNG vehicle with gasoline vehicle range, to include waiting for the pump and paying for the fuel, might approach 10 minutes. DOE has estimated that these stations would dispense an average 220,000 cubic feet of gas per day.[30]

A network of public access, fast-fill service stations will be necessary eventually to enable large-scale replacement of gasoline fuel demand with CNG. Conventional dual-fuel gasoline/CNG conversions have a limited driving range on CNG fuel. CNG fuel availability away from the vehicle's garaging point is necessary to make possible CNG fuel usage during extended, non-commuter driving. Widespread acceptance of CNG vehicles by individuals, particularly individuals without the desire or the means to implement home refueling, will require an expanded network of public access filling stations. This

report therefore considers that a network of fast-fill public access refueling points is vital to widespread public acceptance of CNG as a petroleum fuel replacement. Costs of partial conversion of a gasoline-fueled station to CNG use are considered below. These costs do not include any truck stop conversions to serve heavy-duty vehicles powered by CNG.

Table 5 provides a range of costs to convert a gasoline "island" of four pumping points to CNG usage. It is assumed that the present station location will accommodate the island, and that no acquisition of land will be necessary to facilitate the retrofit. The costs are expressed in a range from lower cost to higher cost options for most of the components.

The compressors considered range from 200 to 300 SCFM of natural gas pumping capacity, for a final storage pressure of 3,600 psi. Compressor costs include starting and cooling systems. Compressor cost is very sensitive to inlet pressure; an inlet pressure range of near atmospheric to 40 psi was assumed.

The range of costs for the compressors given in Table 5 include the cost of a large electric compressor motor. Typically the work of compression at a fast-fill refueling site is done with an electric motor. An alternative to this method might be the use of an industrial natural gas-fueled engine, assuming that any safety or other considerations could be overcome. A recent report prepared for the U.S. DOE, [33] presents a sample calculation for the cost of an industrial natural gas-fueled engine together with a calculation for a comparably sized electric motor. A 200-horsepower engine was estimated to be sufficient for the compressor application given here. The cost of the industrial natural gas engine was calculated to be approximately $21,000; the cost of a 150-kilowatt electric motor for the same application was calculated at roughly $11,000. Subtracting this $11,000 estimated electric motor cost from the compressor cost in Table 5, and adding $21,000 estimated for the industrial natural gas engine would have the effect of increasing the upper bound on the CNG refueling station costs from $396,000 per station to $406,300 per station.

The bottle storage cost was a function of the type of storage vessels used and total storage capacity. At the lower cost end of the spectrum, 20-bottle cascades of 35,000 SCF capacity are assumed to be of sufficient size. The higher cost figure is for 100,000 SCF capacity at 4,000 psi storage pressure. These ASME cylinders are 23 feet in length, 2 feet-3 inches in diameter, and stacked three high. A total of nine cylinders (three banks of three) are necessary to provide this storage capacity. Manifolding expenses for these storage configurations range from $2,250 to $6,800.

Table 5

Costs to Partially Convert a Gasoline Service Station to Fast-Fill CNG Refueling

Capitalized Items	Range of Costs (dollars)
Compressor*	$107,000 - 200,000
Gas storage	25,500 - 99,000
Fast-fill gas metering and dispensing system	24,000
Manifolding	2,250 - 6,800
Sequential, priority panels, wiring, and installation	7,500
Safety valves and devices	12,000
Spare parts	6,000
Gas line connection fees and expenses	2,000
Shipping costs	7,000
Engineering, overhead, and administration	22,000
Buildings	10,000
Land	--
RANGE OF TOTAL COSTS	$225,250 - 396,300

* Includes electric compressor motor.

The costs of the service station retrofit calculated here ranged from $225,250 to $396,300 per station converted. These costs are similar in magnitude to costs in other published reports. In a report prepared for the U.S. Department of Energy, [34] E. A. Mueller costed a CNG fast-/slow-fill refueling station with two nozzles serving 50-60 vehicles at $75,000-125,000. These costs assume a small fleet operation; Mueller's [31] estimated cost of a larger gasoline station retrofit as $321,500 per station. Biederman [29] estimates CNG refueling station costs for medium/large urban public quick-fill stations serving 150-225 vehicles per day over the range of $339,900 to $406,260.

Biederman [29] provides a range of station conversion costs of $175,000 to $193,000 for mixed fast-slow fill conversions serving private fleets of 45-115 light-duty vehicles. Darrow [23] provides a range of $60,000 to $255,000 for the cost of refueling equipment to serve a 100 vehicle fleet. This equipment, however, provides for a mix of fast- and slow-fill capability.

Several potential home compressor packages are mentioned in reference 29, but are referred to as test market applications only. No large-scale use of home CNG refueling has been made and documented. Although very speculative, prices as low as $2,000 for a home compressor have been mentioned.[29]

Advanced natural gas vehicles may have storage pressures as low as 500 psi using adsorbent storage. This form of fuel storage, potentially very advantageous, is not yet commercially viable. Any improvements in natural gas storage technology will have benefits both in vehicle storage and in fueling station storage.

Pipeline Expansion Costs

The increased use of natural gas as a light-duty automotive fuel may have the effect of requiring substantial new investment in pipeline infrastructure. Areas not currently served by a local pipeline distribution infrastructure may have to be supplied with one if natural gas fueling of a significant portion of the locality's vehicles is desired. New end-use loading may impact the entire transmission system, necessitating pipeline expansion and the addition of extra storage capacity.

The U.S. Department of Energy has examined the impact of increased utilization of natural gas as an automotive fuel on the present gas transmission and storage systems.[30] DOE has estimated that the degree of under utilization in the current U.S. gas pipeline transmission system is sufficient to permit the displacement of 1 million bbl/day of petroleum fuel demand in the automotive sector with CNG without the construction of

additional transmission capacity. DOE also assumed that additional storage capacity will not be required nationally. The primary reason for this assumption is that the peak seasonal driving demand for CNG fuel should coincide with the lowest demand period for other segments of the natural gas market.

Local distribution infrastructures may have to be expanded in order to provide gas to public access service stations. Excess capacity would be used and incremental additions to the current distribution system would be made rather than construction of a dedicated distribution network designed for transportation fuel use. The total incremental cost of additions to local infrastructures was estimated by DOE to be upwards from $604 million.

E. A. Mueller has estimated incremental natural gas transmission and storage costs for the U.S. pipeline distribution system assuming the replacement by CNG of 2 million bbl/day of petroleum transportation fuel.[31] This analysis includes costs to service both light- and heavy-duty vehicle demand. Two separate scenarios are considered by Mueller. The first scenario includes distribution system costs to service a refueling network composed of public access service stations and truck stops, as well as a number of private fleet refueling points. The incremental distribution system cost for this scenario was about $3 billion. The second scenario assumed that all refueling occurred at public access service stations and truck stops; increases in distribution costs were estimated at $2.5 billion for this option, which incorporates only the light vehicle portion.

DOE [30] has used E. A. Mueller studies to arrive at the estimates of distribution system incremental costs presented in references 30, 34, and 35. Mueller's higher costs given in reference 31 are associated with expanded scenarios to include heavy-duty truck stop service, involving the replacement of a greater portion of petroleum-based fuel demand than the DOE work.[30]

Capitalized Distribution Costs

The difference between a wholesale price of a fuel and its retail price can be divided into three main components: 1) distribution of the fuel to the service station, 2) service station markup, and 3) taxes. A summary of estimates for capitalized distribution costs relating to both gasoline and CNG fuels is given in Table 6.

The distribution costs associated with gasoline fuel were taken from an earlier EPA position paper.[10] Table 6 presents four separate scenarios for capitalized CNG distribution costs,

Table 6

CNG Fuel Distribution Costs
10-Year Capital Cost Payback
(cents per gasoline gallon equivalent)

Scenario	Local Distribution Costs*	Service Station Conversion Costs**	Service Station Markup	All Taxes	Totals
Lower CNG station cost 10 percent ROR	1.2/ 1.0/ 0.9	6.6/ 5.6/4.9	9	24	40.8/39.6/38.8
Higher CNG Station cost 10 percent ROR	1.2/ 1.0/ 0.9	11.6/ 9.9/8.6	9	24	45.8/43.9/42.5
Higher CNG Station cost CNG compression 10 percent ROR	1.2/ 1.0/ 0.9	11.9/10.1/8.8	9	24	46.1/44.1/42.7
Gasoline	6	--	9	24	39

* CNG figures assume alternately 556,200, 654,300 and 752,500 gasoline gallon equivalents of CNG pumped per station.

** CNG figures do not include operating expenses.

all assuming a 10-year payback period. Local additional distribution costs of $604 million to support a light-duty service station infrastructure are spread over 16,000 service stations, for an approximate average cost of $40,000 per station. A 10 percent rate of return is postulated and an annuity assuming a 10-year payback period is calculated. The annual annuity is divided by three different yearly gas sales estimates: 556,200, 654,300, and 752,500 gasoline gallon equivalents, respectively. These gas sales estimates include the average yearly sales per station estimated by DOE to occur at each of 16,000 light-duty service stations assuming a 1 million bbl/day displacement of petroleum fuel demand by CNG.[30] The upper and lower sales bounds assume 15 percent greater and 15 percent lower sales volumes than the DOE estimate. It should be noted that these estimates are spread over a much higher level of penetration than is required in the President's Clean Air Act Amendments. To the extent that scale is smaller, unit costs will rise.

Two separate service station conversion costs, a higher estimate of $396,300 and a lower estimate of $225,250 have been presented earlier in this report. These two estimates assume that an electric motor is used to compress the natural gas fuel at the service station. If a natural gas-fueled engine is used for compression, we estimate that the higher service station cost would be raised to $406,300. All three estimates are used here; annual annuities assuming a 10 percent annual rate of return are calculated for each scenario. These annualized costs are then dividied by the three different CNG sales volume figures presented earlier.

Taxes are assumed to be applied at the same rate that gasoline taxes are applied, 24¢ per gasoline gallon equivalent. This assumption was made in an earlier EPA position paper.[10]

It is important to note that Table 6 considers only capitalized costs and taxes. Variable operating expenses such as utilities expenses are discussed later in this report. Service station markup includes profit; this amount is the same on a gasoline gallon equivalent basis as reported in the earlier methanol study.[10]

The distribution cost estimates given here are very sensitive to sales volumes of natural gas through the converted stations. If sales volumes per station as large as these postulated here fail to materialize, these costs per unit of fuel delivered could rise in proportion to the decrease in sales volumes.

Gasoline Equivalent CNG Retail Price

The method used here to determine the retail price for a gasoline gallon equivalent of natural gas automotive fuel begins with the determination of a range of prices of natural

gas delivered to vehicle refueling stations. The pricing used here was discussed earlier in this report; the delivered prices include distribution costs to the service station. These costs per gasoline-equivalent are added to the capitalized service station costs developed earlier. Service station operating costs for CNG are developed below. Finally, sales consumption taxes are computed on an energy-equivalent basis with gasoline for CNG fuel.

Table 7 presents a summary comparison of current gasoline and projected natural gas prices.

The current gasoline price rollup was taken from the recent EPA position paper addressing the use of methanol as an alternative fuel.[10] The $1.08 per gallon price is taken from that report; this is the current average retail price of 1 gallon of unleaded, regular gasoline. The current average price of unleaded premium is $1.23 per gallon; weighted average sales of these two gasolines gives a current average price of $1.12 per gallon for unleaded gasoline. Distribution, service station markup, and taxes were taken from Attachment 2 of the aforementioned report.[10]

Using the $2.59 (lower), $4.66 (average), and $5.89 (higher) per million BTU lower heating value prices given earlier for the range of natural gas prices, the conversion to cents per gallon was determined using 114,132 BTU/gallon, a nominal value for gasoline used previously by EPA.[5] This results in values of 30¢/53¢/67¢ per gasoline gallon thermal equivalent.

Capitalized service station costs and taxes for CNG were calculated earlier in this report. Operating and maintenance expenses associated with service station operation were sensitive to the method used to compress the natural gas at the service station (electric motor or natural gas engine). These expenses included compression energy, maintenance, administrative, and other general expenses over the range of CNG sales volumes of 556,200 to 752,500 gasoline gallon equivalents referred to earlier.

The price range for CNG light-duty automotive fuel calculated in this manner is $0.78-1.27 per gasoline gallon thermal equivalent of fuel assuming electric motor compression. For a vehicle with a CNG fuel economy of 17 miles per gasoline gallon equivalent, the fuel price range translates into a cost of between $4.59-7.47 to travel 100 miles. These costs are higher than a recently published estimate of $3.00-5.00 fuel cost to travel 100 miles in a light-duty vehicle equipped to operate on CNG.[36]

Table 7

Gasoline and CNG Energy Equivalent Price Comparison
(dollars per gasoline gallon equivalent)

Cost Classification	Gasoline	Compressed Natural Gas	
		Electric Motor Compression	CNG Engine Compression
Extraction, refining, other	$0.69	--	--
Natural gas delivered to service station	--	$ 0.30/0.53/0.67	$0.30/0.53/0.67
Long-range and local distribution costs	0.06	--	--
Capitalized service station conversion costs		0.05 - 0.12	0.09 - 0.12
Operating expenses		0.08	0.02 - 0.04
Maintenance, admin., and general expenses		0.02 - 0.07	0.03 - 0.08
Service station markup	0.09	0.09	0.09
Taxes	0.24	0.24	0.24
TOTALS	$ 1.08	$0.78/1.07/1.27	$0.77/1.05/1.24

ECONOMIC ASPECTS OF COMPRESSED NATURAL GAS USE

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ENVIRONMENTAL IMPACTS OF CNG USE

Urban Ozone Levels

The primary environmental benefit associated with the alternative fuels program will be significant improvements in ozone levels in the most seriously polluted areas of the country. The clean, alternative fuel advantage over gasoline in terms of urban ozone formation is due to both lower levels of vehicle emissions and the lower photochemical reactivity of these emissions. In the case of CNG, it is the lower levels of photochemically reactive emissions that are of particular importance.

The photochemically reactive fuel-related emissions from CNG-fueled vehicles, for example, consist of mostly nonmethane hydrocarbons (NMHC), compounds with reactivities assumed to be the same as nonmethane hydrocarbon emissions from gasoline-fueled vehicles. The difference is that CNG-fueled vehicle exhaust hydrocarbons are typically 90-95 percent nonreactive methane emissions (5-10 percent NMHC), whereas gasoline-fueled vehicle exhaust hydrocarbons are typically 5-35 percent nonreactive methane emissions (65-95 percent NMHC). Because of this much higher percentage of nonreactive methane, the NMHC emissions of CNG vehicles are much lower than gasoline vehicle NMHC emissions.

Another photochemically reactive compound, formaldehyde, is emitted at very low levels (approximately the same amount is emitted from both CNG-fueled and gasoline-fueled vehicles).

In a test program performed by EPA in 1988, a small fleet of dual-fuel vehicles (vehicles which run on either CNG or gasoline) and one dedicated CNG light truck were tested for exhaust emissions, fuel economy, and performance.[1] In that study, non-methane hydrocarbons were found to be much lower from CNG-fueled vehicles compared to vehicles operating on gasoline as the fuel.

The California Air Resources Board reported exhaust NMHC emissions totaling 9.1 percent of total hydrocarbons from a vehicle with CNG fuel which contained 7.2 percent nonmethane hydrocarbons by weight.[2] Exhaust NMHC is somewhat greater than feedgas NMHC presumably because the exhaust may contain some NMHC from burned lubricating oil. Nonmethane hydrocarbons made up only 3.7 to 6.5 percent of total hydrocarbons in the EPA-tested CNG fuels so the exhaust NMHC in the EPA study might

be expected to be somewhat less than 9.1 percent. Applying the same ratio as that observed in the CARB study yields exhaust NMHC of 4.7 to 8.2 percent of total hydrocarbons. In a subsequent EPA report using the same data, an exhaust NMHC fraction of 10 percent of total hydrocabons was assumed.[3] In the following analysis, the "NMHC = 10 percent of total HC" assumption is used as an upper bound or "worst case," and the "fuel NMHC = exhaust NMHC" assumption is used as a lower bound or "best case" for estimates of NMHC from CNG-fueled vehicles.

In a third EPA report, emission factors are projected for "in-use" dedicated CNG vehicles. This study also uses the previous EPA and CARB-generated data mentioned above. However, since no in-use (high-mileage) data were available, the in-use dedicated-CNG vehicle NMHC exhaust emissions were determined by taking the average of dedicated and dual-fuel laboratory (low mileage) vehicle NMHC data assuming that NMHC = (0.1) THC.[4]

The EPA laboratory data show NMHC exhaust emissions from a dedicated CNG light truck is 0.06 g/mile (assuming fuel NMHC = exhaust NMHC) or 0.14 g/mile (assuming NMHC = (0.1) THC). This test program also shows NMHC exhaust emissions from dual-fuel vehicles operating on CNG average 0.12 g/mile and 0.23 g/mile with the same assumptions, respectively. The projected in-use dedicated CNG vehicle is assumed to have exhaust emissions of 0.186 g/mile NMHC (i.e., the average of 0.14 and 0.23 g/mile).

On a reactivity-equivalent basis, CNG dual-fuel vehicles are projected to emit 36-47 percent less than typical future in-use gasoline vehicles, while optimized dedicated CNG vehicles are projected to emit 80-93 percent less than future in-use gasoline vehicles as shown in Table 8.[5-7]

Passenger cars and light-duty trucks now are typically responsible for approximately 87 percent of all motor vehicle related ozone precursor emissions. If all passenger cars and light trucks in a given metropolitan area were optimized dedicated CNG vehicles that emitted 80-93 percent less ozone precursors than gasoline vehicles, these vehicles would reduce the total ozone impact in that area by an average of 70-81 percent assuming no change in stationary source contributions. Assuming that in the year 2015, gasoline fueled motor vehicles will be responsible for only 20 percent of all ozone precursors in such an area, the replacement of all gasoline fueled vehicles by dedicated optimized CNG fueled vehicles would reduce the total by about 16 to 19 percent.

The ozone precursor emission reductions achievable with the clean, alternative fuels program are a significant portion of what could be achieved by taking the same number of cars off the road, and are much larger than the reductions that would be available from any other motor vehicle control program absent major vehicle use restrictions.

Table 8

Projected In-Use Gasoline VOC-Equivalent
Emissions for Gasoline and Methanol and CNG Vehicles
(grams per mile)

	NMHC	NMHC Reactivity Factor	Meth	Methanol Reactivity Factor	HCHO	Formaldehyde Reactivity Factor	Gasoline VOC-Equivalent
Gasoline:							
- Current Standards	(1.73	x 1.00) + (	0	x 0.19) +	(.007	x 2.2) =	1.75
- Proposed Standards	(0.94	x 1.00) + (	0	x 0.19) +	(.005	x 2.2) =	0.95
FFVs on M85:							
- Readily Feasible	(0.350	x 1.00) +	(0.950	x 0.19) +	(.060	x 2.2) =	0.66
- Optimized	(0.310	x 1.00) +	(0.750	x 0.19) +	(.035	x 2.2) =	0.53
M100:							
- Optimized	(0.05	x 1.00) +	(0.572	x 0.19) +	(.015	x 2.2) =	0.19
Dual-Fuel CNG:							
- Worst Case	(0.604	x 1.00) + (	0	x 0.19) +	(.004	x 2.2) =	0.61
- Best Case	(0.489	x 1.00) + (	0	x 0.19) +	(.004	x 2.2) =	0.50
Dedicated CNG:							
- Worst Case	(0.186	x 1.00) + (	0	x 0.19) +	(.004	x 2.2) =	0.19
- Best Case	(0.057	x 1.00) + (	0	x 0.19) +	(.005	x 2.2) =	0.07

* All fuels except dedicated CNG have hot soak/diurnal, running losses, and refueling losses included in addition to exhaust NMHC emissions. Hot soak/diurnal, running losses, and refueling losses for dual-fuel CNG vehicles are assumed to be nearly equal to those of gasoline-fueled vehicles corresponding to the standards proposed by the President. These values of 0.18 grams per mile for hot soak/diurial, 0.16 grams per mile for running losses, and 0.07 grams per mile for refueling were used as 0.18, 0.16 and 0.03 for dual-fuel CNG. The reduction in refuling losses reflects less fueling with gasoline.

Carbon Monoxide and Oxides of Nitrogen

The exhaust emissions of dual-fuel and dedicated CNG vehicles are difficult to characterize due to the lack of a significant database for either type of vehicle. However, EPA has tested three dual-fuel vehicles: a 1984 Oldsmobile Delta 88, a 1987 Chevrolet Celebrity (2 versions), and a 1987 Ford Crown Victoria (2 versions), and one dedicated CNG 1984 Ford Ranger pickup truck. The exhaust emissions of CO and NOx from these vehicles are discussed together in this section, because current strategies to reduce the emissions of one of these pollutants, tends to increase the emissions of the other.

Dual-Fuel CNG Retrofit Vehicles

The emissions data from dual-fuel vehicles, shown in Table 9, suggest a clear trend with respect to CO emissions.[3] CNG dual-fuel vehicles offer the potential for very significant CO emission reductions. CO emissions from each of five vehicle configurations tested by EPA and CARB (see Table 9) were significantly reduced with CNG, with three of the vehicles emitting near zero CO.[1,8,9] These results confirm both theoretical expectations (better mixing of gaseous fuel, lean operation, lack of fuel enrichment for cold-starting or full power, and better efficiency) and data from test programs involving pre-1981 vehicles.

Another tendency observed in the EPA test program, however, is the CO emission reductions with CNG are not an inherent property of the fuel.[3] As with any fuel, vehicle calibration, and how the vehicle maintains the calibration, are important determinants of CNG vehicle emissions. While all three dual-fuel vehicles tested by EPA ultimately gave very low CO values, two of the three vehicles yielded much higher CO levels when originally tested by EPA in the as-received condition, and the third (a 1984 Delta 88) exceeded the CO emission standard with gasoline. The Crown Victoria vehicle supplier indicated that this car was originally calibrated slightly rich of stoichiometric to achieve low NOx emissions, and had to be recalibrated in order to bring the CO levels down. CO emissions from the Crown Victoria before and after recalibration were 4.3 and 0.4 gpm, respectively. NOx emissions on the Crown Victoria were 0.6 and 0.9 gpm, respectively. The Celebrity CO emissions were 2.6 and 0.0 gpm before and after recalibration, respectively. The corresponding NOx emissions were 1.6 and 1.2 gpm, indicating that a different calibration problem other than air/fuel ratio (e.g. spark timing) could have existed with this vehicle. While the Celebrity exhibited some driveability problems in the high CO mode, the Crown Victoria did not, raising the

Table 9

Exhaust Emissions from CNG/Gasoline Dual-Fuel Cars
(grams per mile over the EPA Federal Test Procedure)[1]

Site	Test Vehicle	Fuel	NMHC[2]	CO	NOx	Eff.1[3]	Eff.2[4]	Accel[4]
EPA	CNG Fuel Sys.	Gasoline	0.30	9.8	0.40	-15%	Base	Base
	1984 Delta 88	CNG	0.25	1.7	1.18	- 7%	+10%	-30%
EPA	Total Fuels	Gasoline	0.27	1.4	1.07	-15%	Base	Base
	1987 Crown Vic.	CNG	0.36	0.5	0.93	-13%	+4%	-27%
EPA	Wisconsin Gas	Gasoline	0.20	1.3	0.60	-15%	Base	Base
	1987 Celebrity	CNG	0.16	0.1	1.19	- 8%	+8%	-31%
CARB	Dual Fuel Sys.	Gasoline	0.36	3.3	0.56	NA	Base	NA
	1983 Ford LTD	CNG	0.35	0.1	0.47	NA	-20%	NA
CARB	Pacific Light	Gasoline	0.26	7.0	0.70	NA	Base	NA
	1985 GMC Pickup	CNG	0.05	0.2	1.06	NA	-20%	NA

[1] Taken from references 1 and 3.

[2] Non-methane HC was calculated assuming that methane was equal to 25 percent of gasoline HC emissions and 90 percent of CNG HC emissions for EPA test vehicles.

[3] Post-conversion energy efficiency over the FTP relative to EPA certification fuel economy data for the specific gasoline vehicle model.

[4] These final two columns use the post-conversion gasoline fuel mode as a baseline for comparison with the CNG fuel mode (negative numbers mean lower efficiency or less acceleration with CNG).

possibility that CO emission increases could go undetected by the vehicle operator in the field. Also, the Crown Victoria was the only vehicle with lower NOx emissions with CNG than with gasoline, but the gasoline NOx levels exceeded the 1.0 g/mile NOx standard.

Another clear emissions trend indicated in Table 9 is that NOx emissions can be increased on CNG relative to gasoline.[3] While two of the vehicles showed slight improvements with NOx on CNG, three of the vehicles suffered increases in NOx. With two of the three dual-fuel vehicles tested by EPA, the increases were large enough to cause the vehicles to exceed the 1.0 gpm NOx passenger car standard on CNG. NOx emissions from CNG vehicles are a concern for two reasons: the desirability of burning CNG fuel at lean air-to-fuel ratios; and because advanced spark timing is often used to compensate for methane's lower flame speed and thereby improve performance. Both conditions in principle will tend to cause higher NOx emissions. CNG Fuel Systems provided data to EPA that suggested that NOx emissions would be increased by 55 percent on the Delta 88 if timing were advanced by a typical margin.[10]

These recent EPA test data suggest the need for further work in this area. The data show that the promise for NOx levels comparable to those from gasoline-fueled cars is there, but clearly more work is needed. Clearly, the dual-fuel vehicles have the potential to provide very large CO emission reductions when operated on CNG. The specific magnitude of CO emission reductions that are achievable will depend on the ability of in-use vehicles to maintain low CO calibrations as well as the need for any design tradeoffs to provide acceptable NOx levels.

Dedicated CNG Vehicles

CNG is such a different fuel than gasoline, that there are many reasons to expect that the optimum engine for CNG will be much different than today's CNG dual-fuel engines. Such an engine would likely provide greater emission reductions and better performance and efficiency than are available from dual-fuel engines.

For improved efficiency and lower CO emissions, the optimum CNG engine should be a high compression, lean burn engine. CNG optimization may be more challenging in this regard than methanol because of its relatively higher flame temperature and slower flame speed. The key to such a design is to reap the efficiency and CO benefits of a high compression, lean burn engine while maintaining NOx emissions within acceptable levels.[3]

The only reported attempt to date to design, build, and evaluate a vehicle which might be an example of an optimized dedicated CNG vehicle was undertaken by Ford Motor Company in 1983. Ford built and leased 27 dedicated CNG Ranger pickup trucks in cooperation with the American Gas Association and member utilities. These trucks were designed to meet the 1984 LDT standards of 0.8 g/mile HC, 10.0 g/mile CO, and 2.3 g/mile NOx. No dedicated CNG vehicles have ever been designed and built to meet the current LDV standards of 0.41 g/mile HC, 3.4 g/mile CO, and 1.0 g/mile NOx or more stringent standards such as are being considered for future vehicles.

The 2.3-liter gasoline engine used in the 1984 Ford Ranger was modified to improve it for CNG utilization including higher compression ratio (12.8:1 instead of 9.0:1) and advanced timing. The original design objective was to match the power output and efficiency of the gasoline Ranger. The final engine met these goals, though with reduced vehicle range.[11] Emissions data from three low-mileage Rangers, two fueled with CNG and one fueled with gasoline, are given in Table 10.[3] These data correlate fairly well with the trends seen with the dual-fuel vehicles discussed above. CO emissions for the two CNG-fueled Rangers are 99 percent lower than the gasoline-fueled Rangers. As mentioned in the previous section, NMHC emissions were 30 percent lower with CNG for both Rangers (the EPA Ranger NMHC number was determined assuming exhaust NMHC equals 10 percent of total HC). NOx emissions with CNG were 73 percent higher on the Ford-tested truck and 82 percent higher on the EPA-tested Ranger.[3]

It is clear that the development of advanced technology CNG vehicles is in its infancy and that the Ford Ranger was simply the first attempt to try to optimize a CNG vehicle. It is very likely that future research may yield improvements in emissions, efficiency, and performance, but the question is whether all can be improved simultaneously and with adequate durability.[3,12] At this time, EPA projects that future advanced technology CNG vehicles will likely be able to provide reductions of over 90 percent for CO emissions. The degree of NMHC and NOx reductions will depend to a large extent on the configuration of the dedicated CNG engine. Given that CNG's octane and flame-speed properties are so different from gasoline or Diesel fuel, it is reasonable to project that an engine optimized to use CNG cleanly and efficiently might not be like a converted gasoline-fueled or Diesel-fueled engine. Most likely the engine will be a naturally aspirated, spark ignition, very high compression ratio engine, with special features for enhancing charge turbulence to speed up heat release. However, a highly boosted engine configuration is also possible, so projecting the likely future reductions in

Table 10

Exhaust Emissions from Low-Mileage CNG and Gasoline Ford Ranger [1]
(grams per mile over the EPA Federal test procedure)

Test Site	Fuel	NMHC	CO	NOx
Ford-1984	Gasoline	0.20	3.2	1.1
Ford-1984	CNG	0.14	0.03	1.9
EPA-1988	CNG	0.14[2]	0.04	2.0

[1] Taken from references 1 and 3.

[2] Non-methane HC was calculated assuming that methane was 90 percent of CNG HC emissions.

emissions is subject to uncertainty. Nevertheless, large reductions (e.g. 80 percent) in the overall NMHC emissions from dedicated CNG-fueled vehicles appear possible since evaporative emissions and running loss emissions are projected to be zero. With careful development we also project that refueling losses of NMHC can also be eliminated. Balancing the large CO and NMHC reductions possible with a dedicated CNG-fueled vehicle with the degree of NOx control necessary will be the most difficult technical area and is clearly one in which more research, development, and demonstration is necessary.

Air Toxics and Global Warming

Air toxic emissions from cars are a function of the fuel type, engine type, and emission control system. For vehicles fueled only with natural gas, several advantages are immediately apparent. CNG contains no benzene, so benzene emissions from refueling running losses and running losses can be assumed to be zero. Exhaust emissions of benzene are very low. Similarly, the emissions of gasoline vapors are zero and the emissions of polycyclic organic emissions are also very low. When considering the toxic emission risk from CNG-fueled vehicles, only exhaust benzene, exhaust 1,3-butadiene, and direct and indirect formaldehyde emissions are of real concern. When the emissions and potency are considered together, the exhaust emissions from CNG-fueled cars can be more than 90 percent lower in toxic impact compared to gasoline-fueled vehicles.[13]

For global warming concerns CNG has an apparent advantage over gasoline due to its hydrogen-to-carbon ratio. However, carbon dioxide is not the only pollutant of concern when global warming is considered. For this analysis, we are assuming that CFC emissions from motor vehicles will be controlled eventually via material substitution. With this assumption, the only pollutants of interest are CO_2, methane (CH_4), and nitrous oxide (N_2O). This analysis is incomplete in that it does not include the global warming impact of fuel production, processing, transport and distribution.

To account for the global warming effects of pollutants other than CO_2, emission of these other pollutants can be converted into CO_2 equivalents by considering their relative global warming reactivity. Relative warming estimates for methane (CH_4) and nitrous oxide (N_2O) appear in reference 14. On a mass basis these were determined to be approximately 50 for CH_4 and 230 for N_2O.

Another evaluation of the global warming impact of CH_4 and N_2O is contained in reference 15. Converting the molecule values from Table 2 of that report, values from 16 to 116 can be associated with CH_4 and 286 to 449 can be associated with N_2O for relative global warming impact.

The estimates of the global warming impact of CH_4 and N_2O relative to CO_2 show a large range. It should be noted that the value of the relative impact is an active area of research and that assigning a single value to the relative impact of CH_4 and N_2O might be controversial at this time. More work is clearly needed in this area to refine these relative impact factors.

The overall global warming index, GWI, will be a combination of the CO_2, CH_4, and N_2O emissions from the vehicle and the relative global warming impact factors assigned to CH_4 and N_2O. In general:

$$GWI = CO_2 + a\ CH_4 + b\ N_2O = GWI\ (a,b)$$

Since the GWI value depends on the numerical values used for a and b, until there is a general consensus on what values should be used, the values in any calculation should be specified to eliminate ambiguity. Values used for this report are: a = 16, 65, and 116, and b = 300.

Constructing the index then requires finding the emission data for CO_2, CH_4, and N_2O from the vehicle of interest.

The values associated with gasoline-fueled vehicles are typically 0.100 grams per mile for CH_4 from reference 16, and 0.015 grams per mile N_2O from reference 17.

Using the data from reference 1, we can construct a GWI (65,300) from the same vehicles using different fuels.

Table 11 illustrates the importance of the emission values in constructing GWI (65,300). Table 11 also can be used to conclude that reliance on CO_2 alone when considering global warming may be insufficient.

It can be seen that the methane emissions using gasoline as the fuel add about 1 percent or 6 GWI (65,300) units to the total on the average, while the methane emissions using CNG as the fuel add about 25 percent or over 150 GWI units to the total. For the assumptions made here, nitrous oxide emissions add about 5 GWI units. Table 11 also shows the sensitivity of the results to the relative importance of the factor a.

Table 11

Calculated Global Warming Index,
Gasoline and CNG-Fueled Vehicles

Vehicle	Fuel	CO_2 (g/mi)	CH_4 (g/mi)	N_2O* (g/mi)	GWI(65,300)
Delta 88	Gasoline	632	0.145	0.015	646
Delta 88	CNG	464	2.456	0.015	628
Crown Victoria	Gasoline	582	0.103	0.015	593
Crown Victoria	CNG	429	3.164	0.015	639
Celebrity	Gasoline	435	0.024	0.015	441
Celebrity	CNG	354	1.478	0.015	455

GWI for Three Values of CH_4
Relative Impact

Vehicle	Fuel	GWI (16,300)	GWI (65,300)	GWI (116,300)
Delta 88	Gasoline	639	646	653
Delta 88	CNG	508	628	753
Crown Victoria	Gasoline	588	593	598
Crown Victoria	GNG	484	639	801
Celebrity	Gasoline	440	441	442
Celebrity	CNG	382	455	530

* N_2O was not measured in this test program; the same nominal value is used for all entries.

In reference 18, a summary of N_2O values is provided. The values in Table 1 of that paper range from 4.8 to 101 mg/mi N_2O, with an average value of 52 mg/mi. Using 52 mg/mi in the calculations in the above table (instead of the 15 mg/mi used) would increase the GWI (65,300) values by approximately 11 units, but it would not change the ranking. Given the spread in the values summarized in reference 18, it would appear, however, that measured N_2O data is a desirable part of any estimates of global warming impact, and measurements of CO_2, CH_4, and N_2O from a variety of engines and fuels would be the minimum needed before a definitive ranking could be attempted. Clearly more work is needed in this area.

ENVIRONMENTAL IMPACTS OF CNG USE

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OTHER ISSUES

Safety

Safety-related issues affect three areas of utilization of compressed natural gas: These broad areas encompass: 1) transport to and storage at the refueling site, 2) vehicle refueling, and 3) onboard vehicle safety. These areas have been addressed by guidelines, requirements, and standards set by the following: U.S. Department of Transportation (DOT), National Fire Protection (NFPA), Compressed Gas Association (CGA), and the American Gas Association (AGA).

DOT is responsible for the safe transport of hazardous materials. Natural gas falls into this designation. DOT guidance establishes both maximum operating and burst pressure for cylinders, the type of testing [1] required before use and periodically during the cylinder lifetime, and allowable contaminants in the compressed natural gas to prevent corrosion. It should be noted that the DOT guidance applies to commercial shipments of industrial gases, not to vehicle fuel containers.

The CGA has published a pamphlet S-1.1 which is used by DOT in its regulation of pressure safety devices. These pressure safety devices are used to reduce cylinder pressures in the event of overfilling or exposure to fire. They keep the cylinders from bursting or exploding. These devices can be a rupture disc, a fusible plug, or a combination of both.

The NFPA established NFPA52 which is a standard for "CNG vehicle fuel systems." This standard established design criteria for gas quality, cylinder location, venting, and support systems in the vehicle. It defines, for example, the level of force that the supporting structure must be able to withstand.

The AGA in their publication No. 1-85, "AGA Requirements for Natural Gas Vehicle (CNG) Conversion Kits," established guidelines for the safe design and construction of CNG vehicles.[2]

Natural gas vehicles have seen significant utilization in fleet-type applications in various parts of the United States and for that matter in various parts of the world. This utilization has lead to a body of experience with vehicle safety that would appear to give CNG a reasonably good safety reputation. It should be considered though that much of the experience in the U.S. is fleet-type with trained operators and refueling attendants. Further studies should be pursued to quantify the affects, if any, of moving from fleet type applications to utilization by the general public.

Reduced Maintenance

The potential of reducing consumer operational cost is generally raised in discussions concerning the use of compressed natural gas. The potential exists but more work is needed to define the benefits accurately; better data are needed.

Such data could be generated through a series of engine dynamometer and vehicle fleet tests each of which could be specifically designed to obtain the necessary comparative data. For example, industry standard tests of oils could be used to compare gasoline only, CNG only, and alternating gasoline and CNG use on properties important for oil quality, lubrication, and wear. Additional engine dynamometer evaluations of spark plug life and valvetrain wear could also be conducted. For vehicle tests, fleets of matched gasoline-only, CNG-only, and alternating CNG and gasoline-fueled vehicles could be run on test tracks or in fleet use such as in taxicabs to generate comparative measured data on fuel consumption, performance, range, oil contaminants, driveability, and engine wear.

Performance and Fuel Economy

The properties of fuel economy and performance are closely related, especially when comparing vehicle operation on two different fuels. It is known that fuel economy is inversely proportional to increases in vehicle weight.[3] Vehicle performance, in terms of the time it takes to accelerate from zero to 60 miles per hour, is greatly influenced by the maximum horsepower of the engine. When comparing the fuel economy of two distinct fuels, it is important to take into account any differences in the power output, inertia weight, and performance of the vehicle(s) used to make this comparison. The parameters of fuel economy, performance, horsepower, and inertia weight are related by the following two expressions which were developed by regression of data measured from 1978 through 1987 model year gasoline-fueled vehicles.[4]

$$T = 0.82(HP/IW)^{-0.82} \quad (1)$$

$$\%\Delta MPG = (0.454)\%\Delta T \quad (2)$$

Where:

T = 0 to 60 MPH performance time (seconds)

HP = Horsepower

IW = Inertia weight (lbs)

%ΔMPG = Percent change in fuel economy (%)

%ΔT = Percent change in 0 to 60 MPH performance time (%)

Dual-fuel (CNG/gasoline) vehicles are slower and less fuel efficient when operating on CNG than when using gasoline due to CNG's poorer volumetric efficiency, and the additional weight of multiple CNG fuel tanks. Since CNG is a gaseous fuel, it displaces air in the combustion chamber, which accounts for lower volumetric efficiency of engines that use CNG. Most dual-fuel vehicles carry at least two CNG cylinder tanks which are usually made of fiber-reinforced steel, though they can be made of aluminum and other composites. The added weight of these tanks plus their fuel capacity must be supported by additional vehicle structure, and secured to the vehicle by brackets. This added structural weight may average roughly 70 percent of the weight of the CNG cylinders.[5]

In the EPA study of light-duty dedicated and dual-fuel CNG vehicles, gasoline-equivalent city fuel economy was improved on CNG relative to gasoline operation on 5 of 6 vehicle configurations tested by amounts ranging from 1 to 12 percent (average of 5 percent).[6] Only the Chevrolet Celebrity in its first calibration test sequence showed a 2 percent decrease in gasoline equivalent fuel economy. These results, though on an energy equivalent basis, are misleading since they do not account for the added weight of the extra fuel systems, or the degraded performance of these vehicles when using CNG.

The dynamometer 5 to 60 MPH acceleration performance measured on the EPA tested dual-fuel vehicles was significantly degraded by an average of about 29 percent on CNG relative to gasoline operation at a constant vehicle weight. Using the equation for fuel economy as a function of vehicle performance

(equation 2), a 29 percent increase in performance time is equivalent to a 13 percent decrease in fuel economy with CNG. Adjusting the average gasoline-equivalent city fuel economy measured on the EPA test fleet for performance yields an average 8 percent decrease in fuel economy for CNG relative to gasoline operation at a constant vehicle weight. Equation 2 predicts the percent decrease in fuel economy is 45.4 percent of the percent increase in performance time since it is based on gasoline vehicle data. Regression of the EPA CNG performance data show this decrease in fuel economy is close to 20 percent of the percent increase in performance time, or a 6 percent decrease in gasoline-equivalent fuel economy for CNG, i.e., 1 percent below gasoline MPG).

In addition to the fuel economy penalty for performance, the CNG fuel economy numbers must be adjusted to account for the higher inertia weight of these vehicles relative to their gasoline-only counterparts. The most commonly used gas cylinders for passenger car CNG fuel are either 14 inches x 40 inches fiber-reinforced steel or 13 inches x 42 inches aluminum composite fuel tanks.[7] Both tanks have a service pressure of 3000 psi. Although the aluminum tanks are lighter weight (roughly 110 lbs. empty) and must meet the same safety standards, the more commonly used production units are the steel tanks at an empty weight of 176 lbs. apiece. The dual-fuel vehicles tested by EPA were equipped with two such tanks each, and the dedicated CNG light-duty truck had three CNG fuel tanks onboard.

As mentioned above, the addition of the CNG fuel tanks for both dual-fuel and dedicated CNG vehicles propagates the need for additional vehicle structural weight to support the weight of the CNG fuel tanks when filled to capacity. The weight of the CNG fuel used in the EPA test vehicles was 0.047 lb/ft^3 and the capacity of the steel containers is 670 ft^3 of CNG. Each tank of CNG has a capacity of slightly more than 30 pounds of CNG fuel. Therefore, the additional weight of just the full steel fuel tanks of the EPA test vehicles was roughly 415 lbs for dual-fuel vehicles and 622 lbs. for the dedicated CNG light-duty truck. The average weight compounding factors, to account for the added vehicle structural support, are 1.7 for dual-fuel vehicles and 1.25 for dedicated CNG vehicles.[5,8,9] Therefore, the total increase in weight of these vehicles over the weight of their gasoline-only counterparts is estimated to be 700 lbs. for dual-fuel vehicles (480 lbs with aluminum) and 775 lbs for the dedicated CNG light-duty truck (530 lbs with aluminum).

Knowing the baseline gasoline vehicle inertia weights and the measured performance for both CNG and gasoline operation, Equation 1 was used to determine the maximum horsepower of the

vehicle engines on both fuels (see Table 12). The CNG engine horsepower was then inserted back into Equation 1 using the higher inertia weights as determined above to estimate the effect on performance of the additional weight. The average effect of additional weight was an increase in 0 to 60 MPH times of 15 percent. Using Equation 2, these degraded performance values translate to an additional fuel economy penalty of roughly 7 percent (3 percent with the EPA regressed CNG data). It should be noted that this increased weight also reduces the fuel economy of the dual-fuel vehicle when operating on gasoline.

Using equation 1 again with the adjusted CNG inertia weights and performance values, yields adjusted CNG engine horsepower values which are on the average over 30 percent lower than the engine horsepower obtained when operating the vehicles on gasoline.

Vehicle Range

The Alternative Motor Fuels Act of 1988, (Public Law 100-494, October 14, 1988), Section 6(a) requires that the Secretary of Transportation establish a minimum driving range of no less than 200 miles for dual energy automobiles when operating on alcohol and an unspecified minimum range for natural gas. This minimum range requirement pertains only to passenger cars and does not apply to light trucks.[10] At present, the minimum range for natural gas dual energy automobiles (those vehicles which operate on natural gas and either gasoline or diesel fuel) being given the most consideration is 100 miles.[11]

Vehicle driving range was not determined during the EPA light-duty CNG and dual-fuel vehicle test program.[12] Vehicles were simply run on CNG over the FTP and HFET cycles (plus 10 accelerations per test sequence) until they ran out of CNG. Vehicles were then refueled if further CNG tests were required, and the vehicle mileage was recorded at the beginning of each test cycle. The exact mileage when vehicles ran out of CNG was not determinable and some vehicles were returned to vehicle suppliers after testing with an undetermined amount of CNG fuel still in their tanks. From the test dates, number of vehicle preps run, and mileage records, the following observed minimum driving range estimates were determined from the EPA test program data.

Two values of range are listed below. The first value is the observed range as discussed above. The second value is a calculated range based on the MPG values from line 10 in Table 12 and an assumed effective tank capacity equivalant to 10 gallons of gasoline. This is about what one would project from two CNG steel fuel tanks (each with the storage equivalent to 5.5 gallons of gasoline) if one would allow for a one-gallon reserve when computing a vehicle's range.

Table 12

Fuel Economy Adjustment for the Additional Weight of CNG/Gasoline Dual-Fuel Vehicles

	Dual-Fuel Vehicle	Delta 88	Crown Victoria1	Crown Victoria2	Celebrity1	Celebrity2
[2]	IW_1	4000	4250	4250	3250	3250
[3]	Tc_1	14.8	13.3	14.2	13.7	14.0
[4]	HP_{CNG1}	117.4	142.1	131.2	104.8	102.1
[5]	Tg	11.4	10.8	10.8	10.6	10.5
[6]	HP_{HO}	161.5	183.2	183.2	143.4	145.0
[7]	$GEFE_1$	15.3	16.0	16.7	19.8	21.9
[8]	IW_2	4700	4950	4950	3950	3950
[9]	Tc_2	16.9	15.1	16.1	16.1	16.4
[10]	$GEFE_2$	14.3	15.0	15.7	18.2	20.2
[11]	$\frac{(10)-(7)}{(7)}$	-6.4	6.1	-6.1	-7.9	-7.9
[12]	HP_{CNG2}	143.9	143.0	135.2	104.7	102.3
[13]	(12)/(6)	1.12	1.28	1.36	1.37	1.42

[1] Dual-fuel vehicles tested by EPA.
[2] Inertia weight of the gasoline certification counterparts to the dual-fuel vehicles in (1) (lbs).
[3] Measured dynamometer 5 to 60 MPH performance of the dual-fuel vehicles using CNG (seconds).
[4] Calculated CNG engine horsepower using (2) and (3) in Equation 1 (HP).
[5] Measured dynamometer 5 to 60 MPH performance of the dual-fuel vehicles using gasoline (HO) (seconds).
[6] Calculated gasoline engine horsepower using (2) and (5) in Equation 1 (HP).
[7] Measured gasoline equivalent fuel economy of dual-fuel vehicles using CNG (MPG).
[8] Adjusted inertia weight of dual-fuel vehicles to account for added fuel tanks, support, etc. = (2) + 700 lbs (lbs).
[9] Calculated 0 to 60 MPH performance of the dual-fuel vehicles using CNG. Uses (4) and (8) in Equation 1 (seconds).
[10] Calculated gasoline equivalent fuel economy of dual-fuel vehicles using CNG showing effect of slower performance (MPG).
[11] Percent change in CNG gasoline equivalent fuel economy due to slower performance (percent).
[12] Calculated CNG engine horsepower using (8) and (9) in Equation 1 (HP).
[13] Ratio of calculated gasoline and adjusted CNG engine horsepowers.

Vehicle Range for Dual Fuel Vehicles

Vehicle	Observed Range During During Laboratory Testing (miles)	Calculated Range Assuming 2 CNG Cylinders and MPG from line 10 Table 12 (1 gallon reserve)
Oldsmobile Delta 88	135	143
Ford Crown Victoria	143	154
Chevrolet Celebrity	85	163

The CNG driving ranges listed above reflect the maximum number of continuous CNG-fueled miles obtained during the EPA test program before a vehicle was either returned to its supplier (Delta 88, Ranger) or refueled for further testing (Crown Victoria, Celebrity). Because mileages were not recorded at the start of vehicle preps, or during performance testing, it is difficult to determine the maximum driving ranges of these vehicles.

With the exception of the Celebrity vehicle, all of the other light vehicles tested by EPA would meet a minimum requirement of 100 miles now under consideration for dual energy natural gas vehicles.

The National Highway Traffic Safety Administration (NHTSA) is in the process of determining the minimum driving range for dual-fuel passenger automobiles as required by the Alternative Motor Fuels Act of 1988.[13] For reference, NHTSA conducted a quantitative study of the driving range of conventional gasoline-fueled passenger cars using the 25 top-selling cars of model year 1988 (63 percent of total 1988 car sales). Their results show an average minimum driving range is 405 miles, with an average lowest combined EPA fuel economy rating of 25.4 MPG, and average fuel tank capacity of 16.1 gallons.

The Alternative Motor Fuels Act of 1988 also defines the gasoline equivalency of natural gas in natural gas fuel tanks. Section 6(c) states that "...100 cubic feet of natural gas shall be considered to contain 0.823 gallons equivalent of (gasoline) fuel...."[10] Since the steel cylinders normally have a capacity of 670 ft^3 CNG (575 ft^3 CNG for aluminum), the CNG fuel tanks when filled to capacity contain 5.5 gasoline-equivalent gallons (4.7 gallons for aluminum).[14]

Assuming the ratio of combined EPA CNG gasoline-equivalent fuel economy to combined EPA gasoline fuel economy observed in the EPA test program (= 1.04 without weight and performance penalties) can be applied to the NHTSA derived 25.4 MPG average 1988 model year gasoline vehicle fuel economy, the combined CNG gasoline-equivalent fuel economy would be 26.4 MPG. Applying

the CNG fuel tank capacity determined above, yields a CNG fuel tank range of 145 miles (124 miles for aluminum). This would mean a vehicle need only be equipped with one large CNG fuel cylinder and one smaller CNG fuel cylinder to meet a minimum driving range of 200 miles. In other words, multiple CNG tank dual-fuel vehicles such as were tested by EPA, could possibly meet a 200-mile range, without additional fuel tanks or other added vehicle weight using the NHTSA methodology.

In a separate study, the Department of Energy has estimated the range of CNG vehicles to be between 80 and 200 miles.[15]

Of course, trying to match the average gasoline vehicle driving range would be difficult for a natural gas dual energy vehicle, and would require at least three (possibly four) CNG fuel cylinders onboard. The doubling of fuel capacity would constrain cargo space considerably, and would require a vehicle inertia weight over 35 percent heavier than that of a comparable gasoline vehicle. Performance would be further degraded and the fuel economy penalty would double that seen with conventional two-tank CNG dual-fuel vehicles.

The setting of a minimum driving range for dual-energy automobiles must balance the needs of the consumer with the technical and economic considerations that are faced by the manufacturers. A low minimum driving range requirement might encourage the production of dual-fueled cars, but lead to dual-fueled cars being designed with such a low alternative fuel driving range that consumers do not buy them or, even if they buy them, infrequently operate them on the alternative fuel. Conversely, an excessively stringent minimum driving range requirement might discourage the production of dual-fueled cars and unnecessarily compromise other vehicle attributes and aspects of performance. Manufacturers would be discouraged by overly stringent minimum range because a vehicle which does not meet the minimum driving range for its type is by definition excluded from the definition of dual-energy or natural gas dual energy vehicle, and is thus unlikely to be built since the manufacturer would not receive any of the benefits or incentives provided by the Act.

From the viewpoint of the consumer, the necessary driving range is dictated by considerations unrelated to AMFA, such as the convenience of a range that permits a typical workweek travel distance, or a daily travel distance for a fleet car. If the majority of consumers would use a dual-energy vehicle in an urban area with more refueling stations or in a fleet application with a central refueling station, a large driving range may be less critical.

Performance and range for CNG-fueled vehicles are important issues. Surveys of CNG-fueled vehicle operators have indicated that the major problems reported were fueling inconvenience, power and performance, and limited range. Assuming the infrastructure can provide convenient, fast fueling, only performance and range remain as major concerns. The more competitive CNG-fueled vehicles are to gasoline-fueled vehicles, the easier the transition to increased use of CNG will be.

Problems with performance and range for today's CNG-fueled cars are primarily attributable to dual-fuel CNG/gasoline applications. If dedicated, optimized CNG vehicles are considered, then there is no reason why such a dedicated, optimized vehicle could not be competitive with today's gasoline-fueled cars. Integration of the fuel tanks and supporting structure into the initial vehicle design instead of just adding the fuel tanks to an existing vehicle is bound to have overall vehicle weight benefits. Current research into advanced adsorbent storage mechanisms for natural gas [16] could also provide substantial benefits in CNG-fueled vehicle range.

One drawback to dedicated CNG light-duty vehicles is the availability of fuel since they require 100 percent access to CNG. To the extent that dedicated CNG vehicles penetrate the market, the volumes of fuel necessitated by demand could increase, which could also increase the costs of infrastructure and fuel delivery.

It appears that the optimized dedicated vehicle is the most attractive use of CNG in the transportation sector. It also appears that more efforts are needed to determine the optimum engine configuration, fuel metering system, and fuel storage technology for this promising fuel. For example, the work being sponsored by the Gas Research Institute in advanced fuel metering, improved storage media, lean burn and fast burn engines, prechamber engines, and other technological advances is the type of work that is necessary to extract the best from natural gas as a vehicle fuel.

The potential for increased efficiency and power for a dedicated CNG application is great. Harnessing this potential is of more than just academic interest since improved engine power and increased engine efficiency will have positive synergistic effects on the two areas shown to require improvement based on dual-fuel results, vehicle performance, and range. Improved engine power will allow the engine to become smaller and lighter and therefore, with the weight compounding effect working in reverse, make the vehicle lighter. Increasing engine efficiency will allow a smaller and lighter gas tank for the same range or more miles of range with the same fuel tank. The synergism appears via the fact that

the lighter weight vehicle, which can be projected from the increased power potential will provide better fuel economy, thus adding to the range, and the smaller and lighter fuel tanks possible with increased efficiency will weigh less, thus resulting in a lighter weight, better performing vehicle.

Fortunately, when freed from the necessity of having to run on gasoline a dedicated CNG system can take full advantage of the attractive characteristics of natural gas. From the standpoint of improving power and increasing efficiency, the most important benefit of natural gas is its very high octane number, well over 100. Values of 120 for both research and motor octane numbers are mentioned in reference 17. Increasing the engine's compression ratio is one method of improving power and increasing efficiency. In reference 17, a compression ratio of 15.5:1 was thought to be optimum for the single combustion chamber geometry considered. This resulted in 15 and 22 percent increases in power and efficiency, respectively, compared to the base case 8.4:1 compression ratio.

Boosting the engine can also improve power and, indirectly via lower idle fuel consumption and lighter engine weight, improve vehicle fuel economy. Boosting the engine can be accomplished via supercharging or turbocharging.

Rapid expansion of a compressed gas provides a cooling effect. The use of rapidly expanded natural gas to cool the intake charge either via a separate heat exchanger or by injecting it into the intake system could increase charge density and offset the volumetric efficiency loss due to use of a gaseous fuel in a premixed charge engine.

Future engine design for natural gas use will also incorporate optimized combustion chamber designs. Designs which provide for a stable reliable ignition of the natural gas/air mixture, while also providing the degree of turbulence needed to enhance flame propagation for efficient heat release patterns, need to be identified.

Considering increased compression ratio, boost, and combustion chamber design, there may be a combination of approaches that yields the best performance and efficiency relationship. This would appear to be a fruitful and needed research area.

In addition to attractive octane characteristics, natural gas also can be operated with dilute air/fuel ratios for improved efficiency. Dilution of the intake charge can be achieved by running a lean air/fuel mixture or by using EGR, or a combination of both. The optimum strategy and calibration of charge dilution for natural gas use of optimized, dedicated engines for light vehicles has yet to be determined. As might be expected, there is an interaction between the degree of

charge dilution and the other engine parameters such as compression ratio, boost, and combustion chamber design discussed previously. Unconventional approaches toward extracting the most from natural gas can also be considered. Storage of the gas at high pressure yields several different fuel metering possibilities all the way from conventional carburetion to direct cylinder injection of the fuel. In reference 18, eighteen different applications of possible natural gas fuel metering systems are listed. While not all of the systems may be practical for light-duty vehicle use, the number of unexplored or partially explored fuel metering systems for natural gas indicates that the optimum system for performance, fuel economy, and emissions has yet to be determined.

Impact On Home Heating

There is some concern that the added usage of compressed natural gas as a motor vehicle fuel could drive up the cost of home heating. In accordance with the provisions of the Alternate Motor Fuels Act of 1988, the Department of Energy is studying this issue and should be publishing a report addressing this subject later this year.

OTHER ISSUES

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